



INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification ⁶ : A62D 3/00	A1	(11) International Publication Number: WO 96/32163 (43) International Publication Date: 17 October 1996 (17.10.96)
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(21) International Application Number: PCT/US96/02158

(22) International Filing Date: 20 February 1996 (20.02.96)

(30) Priority Data:
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98102 (US).(81) Designated States: JP, European patent (AT, BE, CH, DE, DK,
ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published

With international search report.

(54) Title: BIOMASS SOLIDS GASIFICATION SYSTEM AND PROCESS

(57) Abstract

A gasification system (10) and process for gasifying biomass solids. The system includes an auger pyrolysis reactor (16) that is fed with biomass solids. The biomass solids pass rapidly through the auger pyrolysis reactor in a thin film of agitated solids entrained in boiling water vapor and volatilized organic matter. The pyrolysis products pass from the auger pyrolysis reactor directly to a cyclonic gasification reactor (28). Cyclonic motion of the pyrolysis products in the gasifier is induced by tangential introduction of air or oxygen. The entrained solids and pyrolysis gases are converted to fuel gases and tar, which are then fed to a cyclonic separator (36) that is operable as a second stage gasifier to further convert char. Fuel gases are separated and removed for subsequent processing while char is removed and supplied to a char burner (44) to produce process heat.

Russell - We modified the pyrolysis reactor described
in the above document 19 - 1 - 1996.
Lawrence by carrying out pyrolysis to high temperatures
it does not use an initial reactor 28 as in the
above document and then carrying out a second stage
pyrolysis.

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BIOMASS SOLIDS GASIFICATION SYSTEM AND PROCESS

Cross Reference to Related Application

This is a continuation in part of application Serial No. 08/404,747, filed March 15, 1995, in the name of Dennis Moraski and entitled "Process and System for Wastewater Solids Gasification and Vitrification."

Field of the Invention

The present invention relates to the gasification of organic matter, and more particularly to the pyrolysis and gasification of waste biomass solids.

Background of the Invention

Industrial and agricultural processes and municipalities produce large quantities of organic fuels, including wood and agricultural byproducts and municipal and industrial waste sludges. Many techniques for reducing waste volume while recovering energy from organic matter have been developed. These include processes for the gasification of dry solid wastes and dewatered wastewater streams. Gasification has also historically been used to generate fuel gas from low grade solid fossil fuels, such as lignite, peat moss and brown coal.

Conventional biomass gasification schemes suffer from several drawbacks that have limited the present day usage of gasification to dispose of and recover energy from biomass or to convert the energy in low grade fuels to high grade fuel gas. These limitations include necessary restrictions on feed quality, an inability to control the chemical reactions taking place in the gasification reactor, and the large reactor sizes and system complexity required. These limitations reduce the quality of the gas and byproducts produced by gasification, as well as the efficiency and reliability of the

gasification reactors. The construction and operating costs of conventional gasification systems is also prohibitive.

Conventional gasification reactors may operate under gravity flow, or may utilize fixed, moving or fluidized beds. Gasification reactors of the gravity flow type suffer from necessary restrictions in fuel sizing, moisture content and ash content because of the problems associated with gas flow through the reactor. Also, ash slagging and material handling present problems with such conventional reactors. Instead of consuming a low grade readily available biomass (e.g., wet wood, garbage or textile wastes), such gasifiers require the use of dried and sized wood fuel. The costs of such dried and sized wood fuel is substantially greater than low grade fuels, which lowers the economic incentive for using biomass fuels to replace oil and gas.

Conventional gasification reactors of the fixed, moving or fluidized bed type are basically uncontrolled in carrying out the fundamental gasification steps of drying, pyrolysis, char gasification and combustion of char to form ash. Further the water that comes off during the drying step is generally unreacted, and is carried through to the product gas where it can subsequently cause problems associated with condensation, heat exchange and flame temperature when the gas is burned. Pyrolysis as a separate step is often not employed. Where pyrolysis is employed as a step in the gasification scheme, it is neither effectively controlled nor integrated into the system to gain the valuable fuel gases that could potentially be obtained. Additionally, in the oxidation zone of conventional reactor chambers, it is very difficult to precisely control the temperature, material flow and reaction times. Thus it is difficult to produce the maximum conversion or shift of carbon monoxide (CO) to carbon dioxide (CO₂), and of steam to hydrogen (H₂). This results in an inefficient process and an inability to produce fuel gas having the desired characteristics. Thus such conventional air gasifiers typically are capable of producing only low quality fuel gases.

Another drawback with conventional gasifiers is that they do not completely burn all of the char to produce ash, and thus introduce efficiency losses of 2-5% due to unreacted char. There are also problems associated with plasticity flow in the reactor, and slagging also plagues the oxidation zones of most gasifier reactors, resulting in severe operational problems. Many gasifier reactors produce a significant amount of tar and grit. These byproducts must be either dealt with in other parts of the system, or the product gas must be restricted in use to short transfer distances, or to processes that can tolerate a large amount of grit.

Further the gas production rates of conventional air gasifiers are limited because the oxidation and gas/water shift reactions take place only in specific zones of the reactor. Thus the overall size of the reactors can become quite large for a given unit of gas produced, resulting in increased complexity and cost to construct such conventional systems.

Summary of the Invention

The present invention provides a process for gasifying biomass solids. The biomass solids are introduced into a pyrolysis reactor that operates as a thin-film solids boiler. The pyrolysis reactor includes a vessel in which a material conveyor, preferably an auger, is mounted and operated to continuously move the biomass solids through the vessel. Heat is rapidly introduced to the vessel exterior, which is conducted to the biomass solids, causing partial pyrolysis and volatilization, as well as drying of the biomass solids. An agitated stream of gases and entrained solids is produced.

These hot pyrolysis products are then introduced into a cyclonic gasification reactor. Cyclonic motion of the pyrolysis products is induced by tangentially introducing an oxygen-containing gas. The hot pyrolysis products rapidly gasify, forming char and fuel gas.

The char and fuel gas are then conveyed to a cyclonic separator, which is also operable if needed as a second stage gasification reactor, further gasifying the char. Fuel gases are withdrawn from the cyclonic separator, while char is withdrawn and fed to a char burner to produce process heat.

The present process and gasification system constructed in accordance therewith provides for fast, efficient gasification of biomass solids, and is useful both in converting low grade fuels to high grade fuel gas and in recovering energy from industrial, agricultural and municipal wastes.

A medium BTU fuel gas is produced due to the ability to carefully control the various steps of the various stages of the gasification reaction. The size and complexity of the gasification system is reduced relative to conventional systems, as is the cost of construction and maintenance.

Brief Description of the Drawings

The foregoing aspects and many of the attendant advantages of this invention will become better understood by reference to the following detailed description, when taken in conjunction with the accompanying drawings, wherein:

FIGURE 1 provides a schematic diagram of a gasification system constructed to operate in accordance with the process of the present invention;

FIGURE 2 provides a schematic illustration of the coupled auger pyrolysis and cyclonic gasifier reactors of the system of FIGURE 1;

FIGURE 2A and 2B provide schematic cross-sectional illustrations of the reactors of FIGURE 2 taken substantially along lines A-A and B-B, respectively;

5 FIGURE 3 provides a schematic illustration of the cyclonic separator of the system of FIGURE 1; and

FIGURE 4 provides a schematic representation of the char burner of the system of FIGURE 1.

Detailed Description of the Preferred Embodiment

10 A gasification system 10 constructed and operated in accordance with the present invention is shown in FIGURE 1. A feed stream 12 of biomass solids is supplied to the inlet 14 of an auger pyrolysis reactor 16. The auger pyrolysis reactor 16 includes a rotating auger 18 mounted within a casing 20 that is surrounded by a heat exchanger jacket 22. Heat is supplied to the biomass solids as they are
15 conveyed through the pyrolysis reactor 18, rapidly drying the solids and volatilizing organic matter. An outlet 24 of the pyrolysis reactor 16 is immediately adjacent and coupled directly to the inlet 26 of a cyclonic gasifier 28. An air jet assembly 30 introduces tangential streams of air or oxygen into the cyclonic gasifier 28, where it is admixed with, and induces a cyclonic flow in, the pyrolysis gases and entrained
20 biomass solids.

The resulting fuel gas and char exit the cyclonic gasifier 28 in an outlet stream 32, which is supplied to the inlet 34 of a cyclonic separator 36, i.e., cyclone. The cyclonic separator 36 can also be operated, if necessary, as a second stage gasification reactor, as shall be described subsequently. Fuel gases are withdrawn
25 from the cyclonic separator 36 through an outlet 38. Char is removed from the bottom of the cyclonic separator 36 through an outlet 40, and is supplied to the inlet 42 of a char burner 44. The char is then combusted with preheated combustion air introduced through an air jet assembly 46. The resulting combustion products exit the char burner 44 through an outlet 48.

30 The combustion products flow into the inlet 50 of a cyclonic ash separator 52. Ash is removed from the combustion gases and exits through an outlet 54, where it is recovered for subsequent processing. The hot combustion gases exit the ash separator 52 from an outlet 56, and are supplied to the inlet 58 of the heat exchanger jacket 22 on the pyrolysis reactor 16. After flowing through the heat exchanger
35 jacket 22 and providing a substantial portion of its heat to the pyrolysis reactor 16, the combustion gases exit the heat exchanger jacket 22 from an outlet 60. The partially

cooled combustion gases in this outlet stream 62 then flow to a heat exchanger 64, where remaining heat is exchanged to preheat combustion air supplied to the heat exchanger 64 from a blower 66. The cooled combustion gases exit the heat exchanger 64 through outlet stream 68 for further cleaning as may be necessary. The preheated combustion air from the heat exchanger 64 is routed through an outlet stream 70 to both the air jet assembly 46 of the char burner 44 and the air jet assembly 30 of the cyclonic gasifier 28 (as indicated by point "A" in FIGURE 1).

The pyrolysis reactor 16 and gasification reactor 28 of the system 10 are well suited for use in gasifying a wide variety of biomass solids, including dewatered, municipal and industrial waste sludge, waste wood products, and agricultural byproducts. Additionally, low grade fossil fuels such as lignite, peatmoss, and brown coal may be gasified using the system 10.

The pyrolysis reactor 16 is constructed from a sealed screw conveyor having a casing 20 in which the rotating auger 18 is coaxially mounted, as shown in greater detail in FIGURE 2. The auger 18 and cylindrical casing 20 cooperatively define a longitudinal axis 72, about which the screw auger 18 is rotated by a high torque; variable speed hydraulic motor 74. The auger 18 includes a spiral flight 76 that is secured to a central shaft 78. The flight 76 and shaft 78 are sized such that the outer diameter of the spiral defined by the flight 76 closely matches the internal diameter of the casing 20. This permits the flight 76 to scrape and clean the inner wall of the casing 20 during operation. Rather than using a single large pyrolysis reactor 16, it is alternately possible to use multiple smaller auger pyrolysis reactors 16 connected in parallel. The construction and operation of either a single or multiple parallel reactors 16 is the same, and thus only a single reactor 16 is shown and described.

The auger 18 distributes the biomass solids being conveyed through the pyrolysis reactor 16 into a thin-film agitated solids bed, having a depth of approximately 0.1 to 4.0 inches at any location, which enhances heat transfer to the biomass solids. The bed is defined as the space between the flight 76, the auger casing 20, and the shaft 78. This bed thus has a rectangular cross section at any location. The bed is forced spirally and longitudinally along the length of the casing 20 by the constantly turning auger 18. Rotation of the flight 76 during operation provides constant cleaning of the inside heat exchange surface of the casing 20, preventing build up of scale that would inhibit heat transfer. The arrangement has many beneficial aspects of a thin-film solids boiler wherein the vaporization of the gases creates a great deal of turbulence which acts to remove boundary layers and enhances heat transfer.

The pyrolysis reactor 16 is operational in any disposition, from horizontal to vertical, but preferably is positioned on an incline, such that the biomass solids exit the outlet 24 of the reactor 16 at a higher elevation than the inlet 14. Preferably, the pyrolysis reactor 16 is vertically inclined such that the longitudinal axis 72 defines an angle relative to a horizontal plane of from 20 to 70°, and most preferably from 30 to 45°. This vertical orientation causes the conveyed biomass to compact under its own weight to form a plug near the inlet end of the reactor 16, which substantially prevents pyrolysis gases from escaping to the feed section. To enhance formation of this plug, it is preferred that a short section of the flight 76 be removed from the auger 18, as indicated at lower segment 80 of the auger 18 in FIGURE 2. This segment 80 enables the formation of a solid, moving pressure plug around the shaft 78 to block leakage of gases.

To further prevent leakage of materials from the reactor 16, the conveyor or other feed mechanism being used to supply feed stream 12 to the inlet 14 of the pyrolysis reactor 16 is preferably operated at a nominal speed that is slightly greater than the speed of conveyance of solids through the pyrolysis reactor 16. This results in a compacted plug of solid material at the inlet 14 to further prevent gas leakage.

The casing 20 of the reactor 16 is encased in a spiral heat exchanger jacket 22, which is composed of many fins arranged in a spiral pattern. The spiral fins are orthogonal to the exterior of the casing 20, and increase the heat transfer area of the casing 20 by 2 to 5 times. The fins may be spaced as close as 0.1 inch apart, and are in substantially continuous contact with the casing 20. The fins are constructed of a metal having a high heat transfer coefficient and that resists corrosion in an oxidizing atmosphere at elevated temperatures. While a spiral arrangement of the internal fins of the heat exchanger jacket 22 is preferred, it should be apparent that other arrangements are possible, such as circumferentially oriented fins over which the hot combustion gases are baffled within the heat exchanger jacket 22.

The heat exchanger jacket 22 receives hot combustion gases from the char burner 44, which provides the heat for vaporization, i.e., drying, and pyrolysis of the conveyed biomass solids. The hot combustion gases enter through the inlet 58 of the heat exchanger jacket 22, adjacent the outlet 24 of the pyrolysis reactor 16, flowing around the outside of the reactor casing 20 in a direction counter current to the flow of the conveyed biomass solids, and exiting the outlet 60 from the heat exchanger jacket 22, adjacent the inlet 14 of the reactor 16. The combustion gases enter the heat exchanger jacket 22 at a temperature of approximately 1700° to 1800° F, and cool as

they transfer heat to the conveyed biomass solids, leaving the outlet 60 at a temperature of approximately 900° to 1,000° F.

The flow of combustion gases through the heat exchange jacket 22 relative to the auger casing 20 is shown schematically in FIGURE 2A. The casing 20 of the auger 18 provides an enhanced heat exchange surface. The exterior of the casing 20 is directly heated by hot combustion gases flowing through internal passages of the spiral heat exchanger jacket 22 defined by the fins, entering at inlet 58 and exiting at outlet 60. This heat is conducted directly to the entrained agitated solids being conveyed by the auger flight 76.

The conveyed biomass solids stream 12 enters the inlet 14 of the reactor 16 at a temperature of approximately 120° F or less, and is heated to a final temperature at the outlet 24 of the pyrolysis reactor 16 of 600 to 1200° F, and preferably approaching 1200° F. A maximum outlet temperature for the conveyed biomass solids of 1200° F is desired in order to confine operation of the reactor 16 to only drying and pyrolysis, and to not promote the more complex gasification reactions which take place subsequently in the gasification reactor 28.

Pyrolysis takes place in the absence of oxygen, i.e., anoxically, and thus no air or oxygen is supplied to the reactor 16. However, in order to allow variation in the operation of the pyrolysis reactor 16 and precise control of the reactions occurring therein, an option is provided to allow the introduction of air, steam or oxygen to an outlet portion of the reactor 16 through an air injector assembly 82. For example, if it is found necessary in dealing with a particular waste to further elevate the temperature of the pyrolysis product stream exiting from the reactor 16, a controlled quantity of air can be tangentially injected into the pyrolysis product stream to enable controlled combustion of some of the products. However, it is not believed that this addition of oxygen is either necessary or desirable in most instances. Rather, it is preferred for biomass gasification processes that the pyrolysis reactor 16 be maintained in an anoxic condition throughout its length.

The pyrolysis reactor 16 provides for fast pyrolysis that occurs during a short residence time. In particular, the biomass solids are conveyed through the pyrolysis reactor 16 in approximately 0.1 to 5 seconds, rapidly being heated to the ultimate temperature of 600 to 1200° F as the material travels along the length of the reactor 16. The pyrolysis reactor 16 has a very high energy density. This high rate of heat transfer is a result of: (a) the relatively thin (0.1 to 4 inches) film agitated solids bed created by the auger 18; (b) the high temperature differential between the solid biomass feed and the outer heat exchange surface of the casing 20, which ranges from

approximately 600° F at the outlet end of the reactor 16 to approximately 1000° F at the inlet end of the reactor 16; (c) the constant contact of the conveyed biomass solids with the inner heat exchange surface of the casing 20; and (d) the absence of recycled gas or solids through the pyrolysis reactor 16.

5 The pyrolysis reactor 16 results in both drying and pyrolysis of the solid materials being conveyed through the reactor. Initially, gas expansion from vaporization of water within the reactor 16 results in a significant increase in gas pressure, which causes the pyrolysis gases and water vapor to move through and exit the reactor 16 via the outlet 24. The gas flow is self generated, and is driven by
10 volatilization of the water and organic matter. Pressure within the pyrolysis reactor 16 is limited to less than approximately 1 psi. The size of the duct 84 handling the outlet stream from the gasification reactor 28 (to be discussed subsequently) is selected to achieve a downstream gas velocity of 10 to 75 feet per second so that the solid particles can become entrained in the gas flow within the pyrolysis reactor 16
15 and gasification reactor 28 and downstream piping.

Once any aqueous portion of the conveyed biomass solids is vaporized, the organic volatiles are then vaporized within the pyrolysis reactor 16 at temperatures of from 200 to 1200° F as the solid materials continue to move along the reactor 16, absorbing heat from the heat exchanger jacket 22. The water and volatile organics
20 absorb large amounts of heat from the heat exchanger jacket 22 in the process of being vaporized. These liquids and solids serve as a heat sink, and can then provide heat to the entrained solids during the remainder of pyrolysis and gasification. The highly agitated solid particles within the reactor 16 come rapidly into contact with the hot gases and the hot casing 20. The agitation is provided by the constantly moving
25 auger 18 and by the violent boiling action of the water and volatile organic solids that are rapidly expanding in volume by up to 1200 times as they change phase from a solid or liquid to gas, and by the flow of the gases through the remaining solids. The conveyed solids tend to compactly fill the reactor 16 because of the vertical incline of the reactor, thus providing constant contact between the conveyed solids and the
30 heated casing 20.

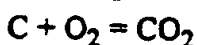
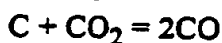
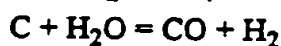
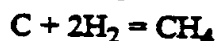
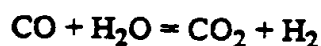
The pyrolysis reactor 16 results in volatilization of from 50% to 95%, and most often 50% to 75%, of the original organic solids entering the reactor 16. This percentage varies depending on the amount of fixed carbon in the feed and the selected process conditions of the reactor 16.

35 The above noted operating conditions for the pyrolysis reactor 16, i.e., short residence time and high temperatures, are selected to yield the highest portion of gas

and the lowest portion of tar and char. Because of the flexibility of the present invention the conditions can easily be changed to maximize the production of char or tars, if so desired, rather than fuel gases. The pyrolysis products leaving the outlet 24 of the pyrolysis reactor 16 nominally consist of approximately 50% water vapor, 35% gas, including volatilized tars but mainly consisting of carbon monoxide and carbon dioxide, and 15% char and unvaporized solids.

Pyrolysis in the pyrolysis reactor 16 is carried out immediately prior to the pyrolysis products being supplied to the gasification reactor 28. This is important because the pyrolyzed carbon produced in the reactor 16 is highly reactive only for a very short period of time. The outlet 24 of the pyrolysis reactor 16 is thus preferably coupled directly to the inlet 26 of the gasification reactor 28, as shown in FIGURE 2. However, it should be apparent to those of ordinary skill in the art that the pyrolysis reactor 16 and gasification reactor 28 could still be utilized suitably with some length of conduit between the two reactors. However, the greater this distance, the less reactive becomes the pyrolyzed carbon, and thus in the preferred embodiment the two reactors are directly coupled together.

As the pyrolysis products flow through the gasification reactor 28, various chemical reactions take place to convert the carbon solids, water vapor, tars and low grade fuel gases to cleaner and more useful fuel gases. The primary reactions are as follows:



These gasification reactions are accomplished by adding air or pure oxygen to the pyrolysis gases, which enter the gasification reactor 28 at approximately 1200°F, resulting in part of the fuel gas and char oxidizing and raising the temperature of the resulting gasification products to an exit temperature of from 1800° to 2200°F.

To provide for introduction of air or other oxygen containing gas to the gasification reactor 28, the air jet assembly 30 is provided. The air jet assembly 30 includes a manifold 84 that feeds pressurized, preheated combustion air from the heat exchanger 64 (FIGURE 1) into a longitudinally spaced series of tubes 86. Each tube 86 is oriented tangentially relative to, and is inserted through, the wall of the cylindrical vessel 88 of the gasification reactor 28. As shown in FIGURE 2B, the tangential flow of introduced air or oxygen imparts a cyclonic motion to the gases and

entrained solids flowing through the gasification reactor 28. In addition to resulting in admixing of the air or oxygen containing gas with the pyrolysis gases and solids, this tangential introduction of high pressure air provides for a much longer process path, and thus more reaction time, as the pyrolysis products pass through the gasification reactor 28. The thorough admixing of air and pyrolysis products at various points along the length of the gasification reactor 28, and the longer process path and residence time provided by the cyclonic action, provides for a high degree of controlled gasification. The introduction of air can be either equal or varied among the tubes 86 to further control the gasification reaction.

It may also be desirable in some instances to introduce steam into the gasification reactor 28. Thus, a steam jet assembly 90, constructed similarly to the air jet assembly 30, is provided. The steam jet assembly 90 also includes a plurality of spaced tubes 92 that are oriented and inserted tangentially within the vessel 88 of the gasification reactor 28. Steam may be required in some instances when fairly dry biomass solids have been fed into the pyrolysis reactor 16, resulting in insufficient water vapor to complete the gasification/shift reactions within the gasification reactor 28. The ability to adjust and control the introduction of air or oxygen and/or steam provides for precise control of the extent of gasification occurring within the gasification reactor 28. The rate of rotation of the auger 18 within the pyrolysis reactor 16 can also be adjusted to control the flow rate of materials through the pyrolysis reactor 16 and coupled gasification reactor 28 for further control. The cyclonic nature of the gasification reactor 28 also provides for forced mixing of solids and heavier gases along the inside wall of the cylindrical vessel 88. The key gasification reagents, i.e., carbon and water vapor, are thus combined at the proper temperature near the inside surface of the vessel. All of these factors result in a high degree of control over the gasification reactions.

To provide for further adaptability and control over gasification, the system 10 provides for optional division of the gasification reaction into two stages. A first stage always occurs within the gasification reactor 28, and an optional second stage occurs subsequently in the cyclonic separator 36.

Fuel gases and char exit the outlet 84 of the gasification reactor 28 in a stream 32, and flow to the cyclonic separator 36. The cyclonic separator 36 is shown in FIGURE 3, and acts to separate the fuel gases, which exit the top of the separator through the outlet 38, from the char, which exits from the bottom of the cyclonic separator 36 through the outlet 40. Tangential feed of the pyrolysis products into the

not needed

separator 36 through the inlet 34 provides the cyclonic separating action of the solids from gases.

As noted previously, the cyclonic separator 36 also provides the option of serving as a second stage gasification reactor. To this end, air or oxygen can be added to the swirling char and gases if necessary to raise the product stream temperature and/or to convert further char to fuel gas. An air jet assembly 94 is provided for this purpose, and similarly to the previously described air jet assembly 30 includes a horizontal series of tubes 96 that can be employed to inject streams of air, oxygen or steam tangentially into an upper portion of the cyclone chamber for further gasification.

Separated char is drawn from the bottom outlet 40 of the cyclonic separator 36, and is fed to the inlet 42 of the char burner 44, which preferably also has a cyclonic action and which is illustrated in FIGURE 4. The cylindrical chamber of the char burner 44 is supplied with preheated air or oxygen from stream 70. The air or oxygen passes into the air jet assembly 46, which injects the air or oxygen into the combustion chamber in spaced tangential streams through tubes 98. As noted previously, the combustion air flowing into the jet assembly 46 is supplied by the blower 66, and has been preheated in the heat exchanger 64 by the fuel gases flowing from the cyclonic separator 36.

The cyclonic char burner 44 is a high-temperature device in which high-velocity, swirling combustion air is used to completely combust remaining char. The resulting hot combustion gases and ash exit the char burner 44 at a temperature of approximately 1800°F, and are supplied to the inlet 50 of the ash separator 52. Ash is removed from outlet 54, and the hot combustion gases are supplied to the heat exchanger 22 of the pyrolysis reactor 16, as previously described.

Start-up of the system 10 requires the use of additional make up fuel, such as liquefied petroleum gas, oil or natural gas, to be fed into the burner 44 to achieve the desired temperature in the pyrolysis unit 22. Once the systems are up to operating temperature, the use of make up fuel is terminated. The system 10 utilizes components that are highly compact, which is particularly well suited for small and medium sized applications ranging from 5 to 500 MBtu/hour of feed gross heat value.

While the preferred embodiment of the invention has been illustrated and described, it will be appreciated that various changes can be made therein without departing from the spirit and scope of the invention. Thus it is intended that the scope of letters patent granted hereon be limited only by the definitions contained in the appended claims.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. A process for gasifying biomass solids, comprising the steps of:
partially pyrolyzing the biomass to produce hot pyrolysis products;
introducing the hot pyrolysis products into a cylindrical gasification reactor;
and
inducing cyclonic motion of the hot pyrolysis products within the gasification reactor while introducing an oxygen-containing gas to gasify the pyrolysis products, producing fuel gas and char.
2. The process of Claim 1, wherein cyclonic motion is induced within the gasification reactor by introducing the oxygen-containing gas in a tangential stream.
3. The process of Claim 2, wherein the step of pyrolyzing the biomass solids is completed in a pyrolysis reactor that is coupled immediately downstream of the gasification reactor, with an outlet of the pyrolysis reactor serving directly as the inlet of the gasification reactor.
4. The process of Claim 3, wherein the step of pyrolyzing comprises conveying the biomass solids through a pyrolysis reactor comprising a rotatable auger mounted within a heated casing for transfer of pyrolysis heat to the biomass solids.
5. The process of Claim 4, further comprising the steps of:
separating char from the fuel gas produced during gasification;
burning the char to produce hot process gas; and
exchanging heat from the hot process gas to the pyrolysis reactor to supply the heat of pyrolysis to the biomass solids.
6. The process of Claim 1, further comprising the steps of:
separating char from the fuel gas produced during gasification;
burning the char to produce hot process gas; and
exchanging heat from the hot process gas to supply the heat of pyrolysis to the biomass solids.
7. The process of Claim 1, further comprising:
supplying the fuel gas and char from the gasification reactor to a cyclonic separator; and

further gasifying the char while separating a remaining portion of the char from the fuel gas.

8. A process for pyrolyzing biomass solids, comprising:

introducing the biomass solids into a thin-film solids boiler comprising a vessel in which a material conveyor is operably mounted, wherein the material conveyor is operated to continuously move the biomass solids through the vessel boiler; and

rapidly introducing heat to the biomass solids within the vessel, causing at least partial pyrolysis and volatilization of the biomass solids so that the biomass solids are continuously agitated and entrained in a resulting gas stream during pyrolysis.

9. The process of Claim 8, wherein the material conveyor utilized comprises an auger that is encased and rotated within a cylindrical vessel.

10. The process of Claim 9, wherein the auger and vessel define a solid bed thickness of from 0.1 to 4.0 inches during pyrolysis.

11. The process of Claim 9, further comprising introducing heat to an exterior wall of the vessel so that heat is transferred from an interior wall of the vessel directly to the agitated biomass solids.

12. The process of Claim 11, further comprising scraping the interior wall the vessel with an auger flight during pyrolysis to prevent fouling of the reactor.

13. The process of Claim 9, wherein the residence time of biomass materials passing through the boiler is less than or equal to 10 seconds, in which time the biomass materials are substantially pyrolyzed to form gases and char.

14. The process of Claim 9, wherein the auger and vessel used for pyrolysis cooperatively define a longitudinal axis that is disposed at an incline of from 20° to 70° relative to horizontal.

15. The process of Claim 14, wherein the longitudinal axis is disposed at an incline of from 30° to 45° relative to horizontal.

16. The process of Claim 14, wherein a lower portion of the auger is devoid of an auger flight, creating a plug of solid biomass around the auger to reduce leakage from the vessel.

17. The process of Claim 14, further comprising feeding biomass solids to the auger reactor at a higher speed than a speed at which the biomass solids flow through the vessel, creating a compacted plug of biomass solids at an inlet to the vessel to reduce leakage from the vessel.

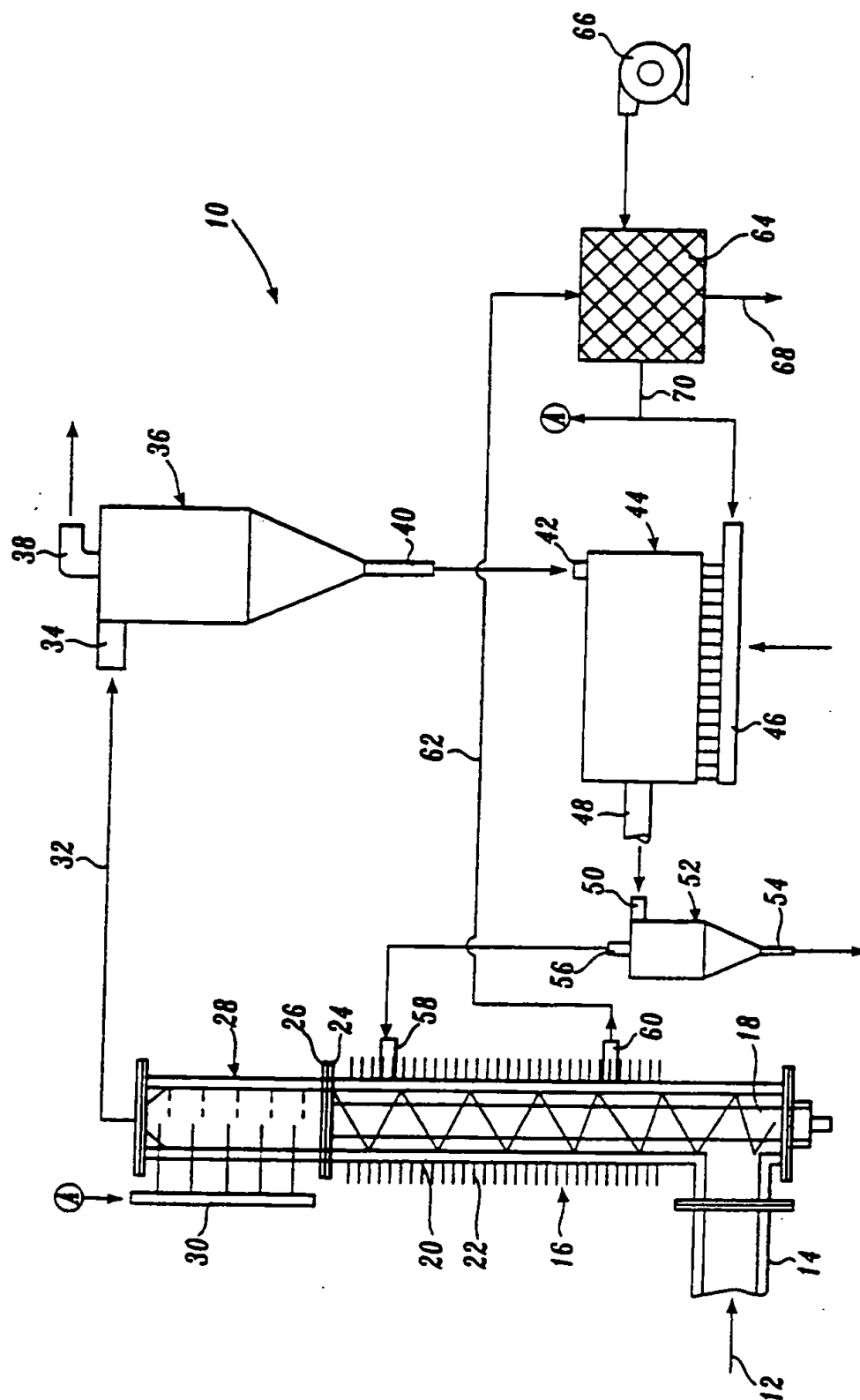


Fig. 1.

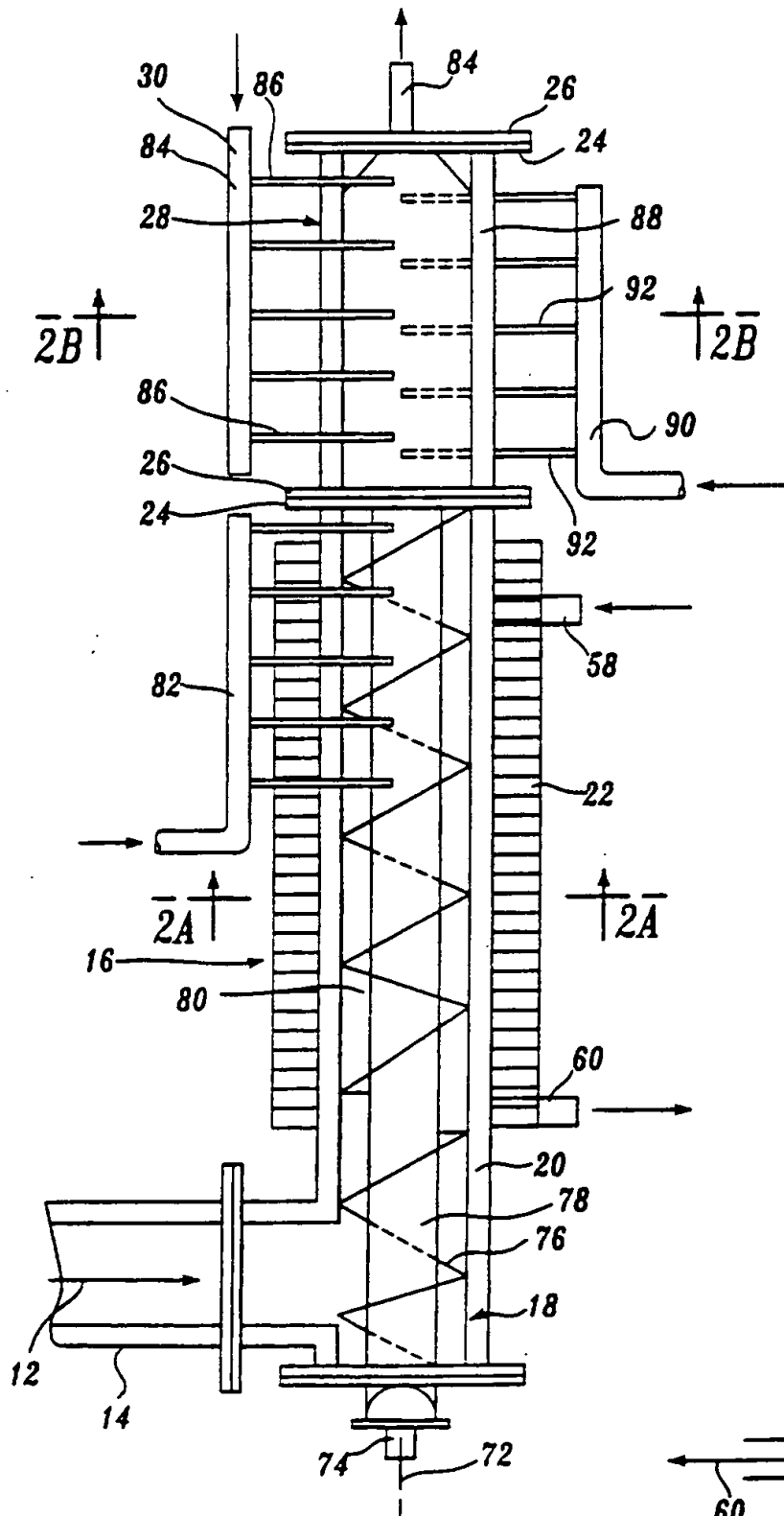


Fig. 2.

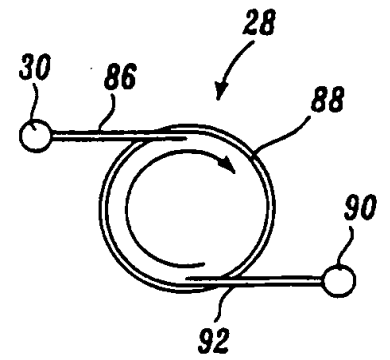


Fig. 2B.

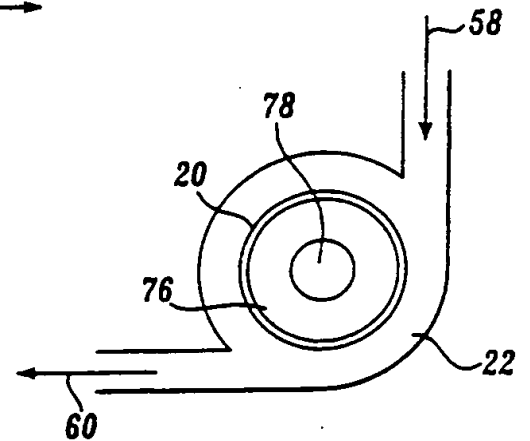
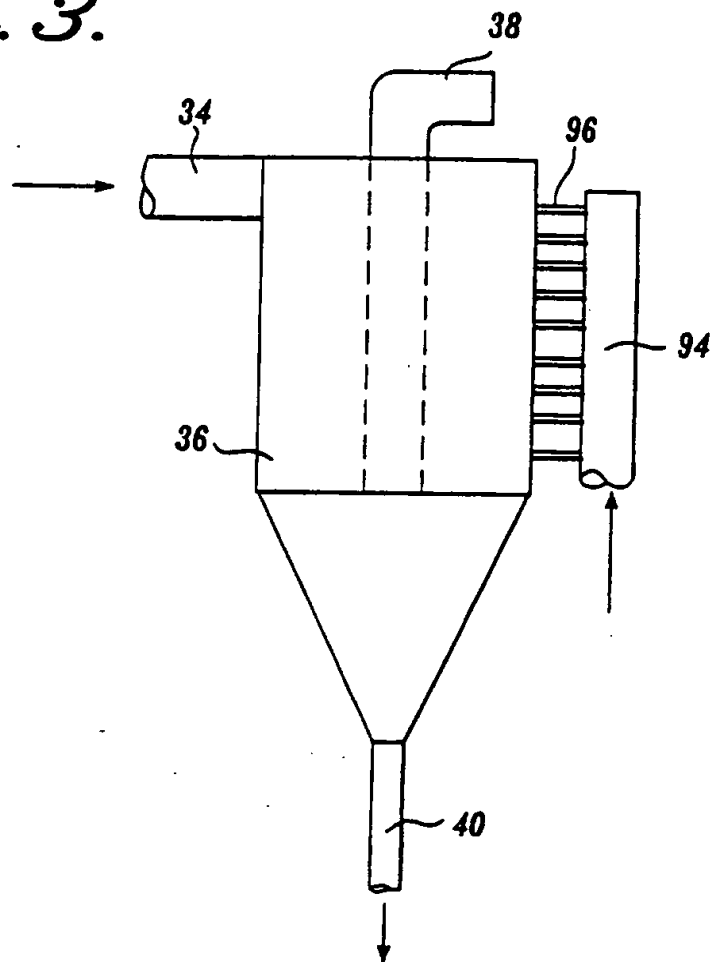
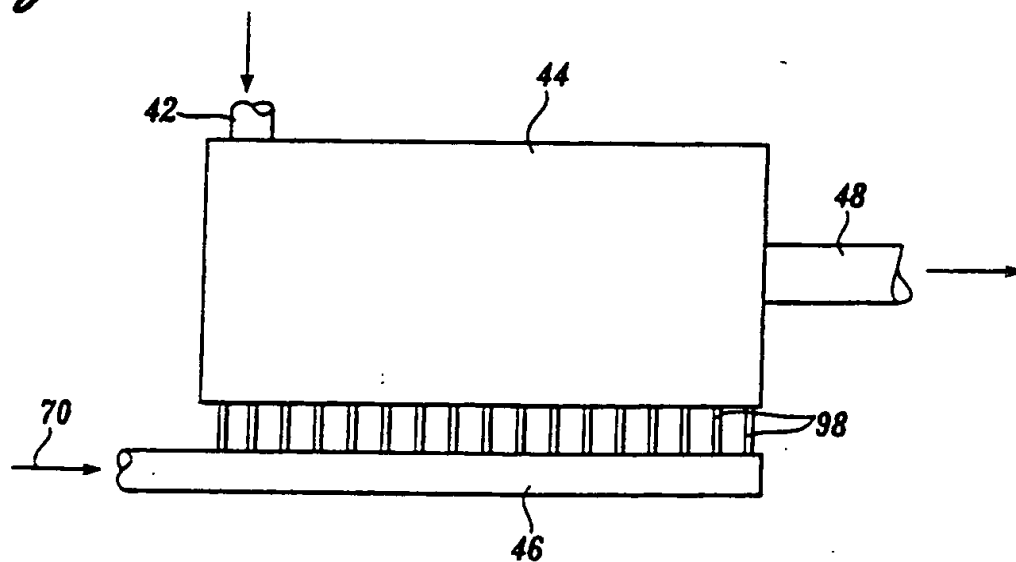


Fig. 2A.

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Fig. 3.*Fig. 4.*

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US96/02158

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) : A62D 3/00

US CL : 588/213

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : Please See Extra Sheet.

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS, WP1D5

Biomass, gasification, fluidize, auger, cyclonic, pyrolysis

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US,A, 5,279,234 (Bender et al) 18 January 1994, abstract; col. 2, lines 64-66; col. 3, lines 1-26; col. 7, lines 16-19.	1-7
Y	US,A, 4,497,637 (Purdy et al) 05 February 1985, claim 1.	1-7
Y	US,A, 4,738,205 (Beierle et al.) 19 April 1988, col. 1, lines 64-67; col. 2, lines 38-42; abstract.	8-17
A	US,A, 4,162,655 (Bozdech et al.) 31 July 1979.	none

☒ Further documents are listed in the continuation of Box C.
 ☐ See patent family annex.

* Special categories of cited documents:	T	later documents published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
A document defining the general state of the art which is not considered to be of particular relevance	X	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
E earlier document published on or after the international filing date	Y	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
L document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	Z	document member of the same patent family
O document referring to an oral disclosure, use, exhibition or other means		
P document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search

28 JUNE 1996

Date of mailing of the international search report

11 JUL 1996

 Name and mailing address of the ISA/US
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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US96/02158

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US, A, 4,846,668 (Beierle et al.) 11 July 1989.	none

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US96/02158

B. FIELDS SEARCHED

Minimum documentation searched

Classification System: U.S.

X
X

I
X

6

A62D 3/00

588/213

U.S.

588/210,212,213,219,225,226,227 1101 346; 204/157.15, 158.20, 158.21

NONE

YUS.A. 5,279,234 (Bender et al) 18 January 1994, abstract; col. 2, lines 64-66; col. 3, lines 1-26; col. 7, lines 16-19.1-7

YUS.A. 4,497,637 (Purdy et al) 05 February 1985, claim 1.1-7

AUS.A. 4,162,655 (Bozdech et al.) 31 July 1979.none

19 APRIL 1996

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/US96/02158

AUS. A. 4,846,668 (Beierle et al.) 11 July 1989. none

X

APS, WP1D5

Biomass, gasification, fluidize, sugar, cyclonic, pyrolysis
X

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